AD-A078 840 HULL CORP HATBORO PA THINCO DIV F/G 9/1
PROGRAM TO DESIGN, DEVELOP, FABRICATE AND DELIVER THIN FILM CHI--ETC(U)
NOV 79 S T CHEN N62269-78-C-0312
UNCLASSIFIED NADC-78111-40 NL

1 OF 1
AD
A078840

END
DATE
FILMED
1-80
DDC

NADC REPORT NO. 78111-40

PROGRAM TO DESIGN, DEVELOP, FABRICATE AND DELIVER THIN FILM CHIP INDUCTORS SUITABLE FOR HYBRID CIRCUIT APPLICATIONS

(14)

NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PA. 18974

CONTRACT N62269-78-C-0312

ADA078820

FINAL REPORT

PREPARED BY

HULL CORPORATION, THINCO DIVISION
Davisville Road
Hatboro PA 19040

411513

November 13, 1979

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

79 12 28 009

DISTRIBUTION LIST

	No. of Copies
NAVAIRSYSCOM	
AIR-360F	1
AIR-53341E	1
CNO	
OP-987C	1
OP-943	1
OP-942C3	1
0312	1
NAVELEX, 310	1
NOSC	1
NAC	1
NUSC	1
NWC	1
NRL	1
ONR	1
DDC	12

Accession For

A

Unclass

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

14 REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 18 NADC-78111-40

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): 6 PROGRAM TO DESIGN, DEVELOP, FABRICATE AND DELIVER THIN FILM CHIP INDUCTORS SUITABLE FOR HYBRID CIRCUIT APPLICATIONS.

5. TYPE OF REPORT & PERIOD COVERED: 9 Final Report.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): 10 Dr. Stephen T. C. Chen

8. CONTRACT OR GRANT NUMBER(s): 15 N62269-78-C-0312

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Hull Corporation, Thinco Division
Davisville Road
Hatboro, PA 19040

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
62762N, RF COMM. TECH.
17 WF62580000 BW501

11. CONTROLLING OFFICE NAME AND ADDRESS:
NAVAIRDEVCEN
CODE 4041
Warminster, PA 18974

12. REPORT DATE: 11 1 Novem[redacted]79

13. NUMBER OF PAGES: 28

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 12 32

15. SECURITY CLASS. (of this report): Unclass

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report):
Approved for Public Release; Distribution Unlimited

16 F62580

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
Thin Film Inductors, Chip Inductors, Hybrid Circuit Inductors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Inductors were fabricated using thin film techniques. The winding of an inductor was formed by depositing alternate layers of metal and dielectric material in steps of one-half turns. The optimization of Q-factor and self-resonant frequency were discussed. Comparison of circular and square geometry were made indicating that the circular one was preferred. Use of magnetic ferrite substrate to increase the inductance and the Q-factor has been achieved. Different methods for the measurement of inductance and Q-factor were described and the results of the measurements of a thin film inductor were given.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

Unclass

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

411513 Gm

TABLE OF CONTENTS

FINAL REPORT

1.0 INTRODUCTION

The Hull Corporation, Thinco Division, has been awarded a contract by the Naval Air Development Center to develop and fabricate thin film chip inductors for hybrid circuit applications. The project consisted of two phases. In Phase I, the objective was to develop inductors having inductance values in the range of 25 to 100 nanohenries, and in Phase II, the range of 250 to 1000 nanohenries.

The inductors were fabricated by depositing alternating layers of metal and insulating material. To form a helical winding, the coil was deposited in increments of one-half turns. The deposition sequence is shown in Fig. 1.0-1. The geometry of the inductor can be either circular as shown, or rectangular. The terminals of the inductor are located at opposite sides of the inductor for making electrical connections.

The most important parameters of an inductor are the Q factor and the self-resonant frequency. The effort on this project has been mainly devoted to the improvement of these parameters. For high inductance values, magnetic material is used to increase the inductance to achieve the high inductance value required.

Accurate measurement of the parameters of an inductor at high frequencies presents considerable difficulties. Effort has been spent to devise various methods of measurement in an attempt to find the best approach.

2.0 OPTIMIZATION OF INDUCTOR PARAMETERS

The two important electrical parameters of an inductor are the Q factor, and the self-resonant frequency (SRF). It is desirable to have the highest values of these parameters possible.

2.1 Q-FACTOR

The Q-factor of an inductor is defined as the ratio $\omega L/R$, where ω is the angular frequency, L the inductance, and R the effective resistance. The effective resistance is contributed by the series resistance of the inductors and the parallel resistance due to the losses in the dielectric between turns. The equivalent circuit is shown in Fig. 2.1-1, where R_s represents the effective series resistance at the angular frequency ω, R_p the parallel resistance, and C the distributed capacitance. The resultant Q-factor is approximately:

$$Q_e = \frac{Q_1 \quad Q_c}{Q_1 + Q_c}$$

where

$$Q_1 = \frac{\omega L}{R_s} \quad , \quad Q_c = \omega C R_p$$

Therefore, to achieve a high value of Q-factor the series resistance R_s must be kept as low as possible and the parallel resistance, R_p as high as possible. For a given geometry of an inductor the series resistance is decreased by increasing the thickness of the metal. Aluminum was selected for the conductor deposition because of its relatively high conductivity and ease in deposition. The maximum thickness of aluminum is limited by skin-effect and the deposition process. The skin-effect of aluminum at 1 GHz is approximately 2.7 microns. The thickness of aluminum for most of the inductors fabricated was 3 microns. Therefore, the series resistance of the inductors operating at 1 GHz and below is not skin-effect limited.

To reduce the loss in the dielectric which contributes to the parallel resistance in the equivalent circuit of the inductor, considerable amount of effort has been devoted in the search and experimentation of a superior dielectric material. A number of them have been investigated. For the purpose of evaluation, capacitors were fabricated by depositing alternate layers of aluminum and the dielectric materials under evaluation. The Q-factors of the capacitors was then measured for comparison. The dielectric materials evaluated were silicon dioxide (SiO_2), silicon monoxide (SiO), magnesium fluoride (MgF_2), and Pyrex 7740. Both the SiO_2 and SiO gave high losses after deposition, MgF_2 has lower losses but developed fine cracks after deposition. Pyrex 7740 was discarded because of higher losses and dielectric constant. After exhaustive search for a better dielectric material, a single phase ceramic dielectric material was found to be the best for the fabrication of inductors. The dielectric constant is approximately 4 and a very low loss was maintained after being deposited by electronic beam method. The material is designated by Thinco T-3.

2.2 SELF-RESONANT FREQUENCY

To increase the self-resonant frequency (SRF), the distributed capacitance of the inductor must be kept as low as possible. The distributed capacitance is approximately

$$C_d = \frac{C_t}{N-1}$$

where C_t is the capacitance between two adjacent turns of the inductor and N is the number of turns of the inductor. The value of C_t is given by the following expression

$$C_t = 0.2246 \frac{\epsilon A}{t} \text{ picofarads}$$

where ϵ is the dielectric constant of the dielectric, A the area in square inches of one turn of the inductor in the plane parallel to the substrate, and t the thickness in inches of the dielectric between two adjacent turns. Hence, to increase SRF the width of the conductor should be as narrow as possible but is limited by the increase in resistance. The dielectric constant should be lowest but the material must also have low loss factor. The dielectric layer between two adjacent turns should be made as thick as possible but is limited by the deposition process. In most of the inductors fabricated, the thickness of the dielectric was chosen to be 4 microns. Silicon Dioxide (fused quartz) has a dielectric constant range of 3.75 to 4.1. Thinco T-3 material has a higher dielectric constant which is in the range of 4.0 to 4.6 but it was chosen because of its low loss property maintained after being deposited.

3.0 GEOMETRY OF THIN FILM INDUCTORS

The inductors of circular geometry is shown in Fig 1.0-1 but a rectangular geometry is also feasible. The comparison between the two geometries is made with the assumptions that both types will require the same chip size and the same conductor width. The dc resistance and the distributed capacitance of the round and square geometries are compared. It is shown in following sections that both the parameters are lower for the circular geometry and was chosen on this basis.

3.1 RESISTANCE COMPARISON

Referring to Fig. 3.0-1 the dc resistance per turn of an inductor of the circular geometry is

$$R_c = \frac{2\pi}{\ln \frac{r_1 + w}{r_1}} \quad \frac{\rho}{t}$$

where ρ is the resistivity of the metal and t is the thickness of the metal deposition. The resistance of that of the square geometry is

$$R_s = \left(8\frac{r_1}{w} + 4k \right) \frac{\rho}{t}$$

where k is the resistance factor of a corner square and has an empirical value of 0.55. The following table gives the comparison of the two cases for several values of the ratio r_1 to w.

	R_{ct}/ρ	R_{st}/ρ	R_c/R_s
$r_1 = w/2$	5.7	6.2	0.92
$r_1 = w$	9.1	10.2	0.89
$r_1 = 2w$	15.5	18.2	0.85
$r_1 >> w$			0.79

For large ratio of r_1 to w the resistance of a circular geometry is about 21% lower.

3.2 COMPARISON OF DISTRIBUTED CAPACITANCE

In comparing the distributed capacitance it is assumed that the dielectric thickness and number of turns are the same in both cases. The area of two adjacent turns of a circular inductor is

$$A_c = \pi w(2 r_1 + w)$$

and that of the square geometry is

$$A_s = 4w(2 r_1 + w)$$

The ratio of the distributed capacitance of the circular geometry to that of the square geometry

$$\frac{C_c}{C_s} = \frac{\pi}{4} = 0.79$$

4.0 CALCULATION OF INDUCTANCE

The inductance is calculated by using Nagaoka's formula given by Grover.[1] The equation is

$$L = 2\pi^2 \left(\frac{2a}{b}\right) N^2 K \text{ nanohenries}$$

where L = inductance
a = geometric mean radius of the winding
b = length of the winding
N = number of turns
K = factor of end effects

K is a function of the shape ratio 2a/b and is given by the following series

$$K = \frac{2\beta}{\pi}\left[\left(\ln\frac{4}{\beta} - \frac{1}{2}\right) + \frac{\beta}{8}\left(\ln\frac{4}{\beta} + \frac{1}{8}\right) - \frac{\beta^4}{64}\left(\ln\frac{4}{\beta} - \frac{2}{3}\right) + \frac{5}{1024}\beta^6\left(\ln\frac{4}{\beta} - \frac{109}{120} - \cdots\right]\right.$$

in which $\beta = b/2a$. This series converges rapidly and three terms is usually sufficient.

The geometric mean radius, a is obtained from the following relation

$$\ln a = \ln r_1 - \ln \zeta$$

where r_1 is the inside radius and ζ is given in a table by Grover.[1]

The actual inductance measured at 50 MHz on a Hewlett-Packard Model 4342A Q-Meter is lower than the calculated value but

1 Grover, F.W., Inductance Calculations, D. Van Nostrand Co., New York, 1946.

differs by a fixed factor. The possible reason for the difference is due to the fact that the deposited conductor width is wider than that dimension of the deposition mask due to spreading of the metal deposition and the fact that the diameter of the winding is much greater than the length of the coil so that the factor of end effect becomes inaccurate. The difference in calculated and measured value, however, is found to be a constant ratio for all different number of turns of interest (1½ to 12½). For the L-55c inductors (r_2 = 27.5 mils, r_1 = 17.5 mils) the calculated value is greater than the measured value by a factor of 1.76 and for L-100c inductors (r_2 = 50 mils, r_1 = 35 mils), the factor is 1.85. By including the correction factor in the inductance equation, the inductance value can be calculated and agrees well with measured value for any number of turns in the inductor.

5.0 FABRICATION TECHNIQUE AND PROCESS

The inductor is formed by depositing alternate layers of metal and dielectric on a substrate (10 mil thick alumina) in a vacuum system. The sequence of deposition is shown in Fig. 1.0-1. The sequence of deposition is summarized as follows:

Step 1. Deposition of metal for the starting terminal and the first half turn (Mask No. 1).

Step 2. Deposition of first dielectric layer over the first half turn of metal (Mask No. 2).

Step 3. Deposition of second half turn of metal (Mask No. 3) joining the first half turn.

Step 4. Deposition of second dielectric layer over the second half turn of metal (Mask No. 4).

Step 5. Deposit the third half turn of metal joining the second half turn of metal (Mask No. 5).

Step 6. Repeat Step 2 if total number of turns is more than 1½.

Step 7. Repeat Step 3 if total number of turns is more than 1½.

The process is continued until the total number of turns is reached. The process ends after the last odd number of half turns is deposited. Therefore, the total number of turns is always an integer of half turns, that is, 1½, 2½, 3½, etc.,

Step 8. Deposit the last half turn and the end termination (Mask No. 6).

Step 9. Deposit dielectric to cover the entire inductor using Masks No. 2 and No. 4.

The metal and dielectric patterns were deposited onto a 2" x 2" x .010" alumina substrate through six different masks as indicated above. Each mask contains an array of identical patterns of metal or dielectric. There are 196 L-100c inductors or 576 L-55c inductors, and 1,156 L-30c inductors on each substrate. Precise registration must be maintained of the masks to the guide pins. The six masks were mounted on a round rotating carrier in a NRC 3176S vacuum system using a stainless steel bell jar 25 inches in diameter by 30 inches high. Two movable crucibles were used, one for aluminum and the other for the dielectric. Feeding mechanisms were provided to feed the aluminum wire and dielectric chips to replenish the materials in the crucibles during deposition. The entire array of inductors were completed without any interruption of the vacuum system.

An electron beam system (Airco-Temescal CV-14 unit) was used for the energy source of deposition which is capable of producing a maximum beam power of 14 KW. To reduce the spreading of the deposited material, the masks must be kept at close contact with the substrate. Magnetic stainless masks were used in conjunction with a permanent magnet assembly for pulling the masks against the substrate tightly. The thickness of depositions was monitored by a quartz crystal rate and thickness controller.

The array of inductors was heat treated at 450°C in a dry nitrogen atmosphere after the depositions were completed to reduce the electrical resistance at the metal interfaces and relieve the mechanical stresses in the inductors. The substrate was then cut to individual inductor chips by a dicing saw.

6.0 INDUCTANCE ENHANCEMENT WITH FERRITE SUBSTRATE

To achieve high inductance values, as much as 1.0 microhenry, magnetic ferrite substrate was used. By depositing inductors directly on ferrite instead of alumina substrate, the inductance was increased. A development program was carried out, in cooperation with Trans-Tech, Inc. to produce a suitable ferrite material for this application. A planar hexagonal ferrite was chosen. Experiments in the firing temperature were carried out to minimize the losses at high frequencies. Using the ferrite substrate, the inductance was increased by about 60%. This large increase is due to the fact that the length to diameter ratio of the thin film inductors are very low so that the majority of the magnetic flux lines are close to surface of the substrate.

The inductance on a non-magnetic substrate can be expressed as

$$L = \frac{0.4 \pi N^2 A}{\ell}$$

where N = number of turns
A = equivalent cross-sectional area of the magnetic flux path
ℓ = equivalent length of the magnetic flux path

With magnetic substrate the inductance is

$$L' = \frac{0.4 \pi N^2}{\frac{\ell_a}{A_a} + \frac{\ell_m}{\mu_m A_m}}$$

Where ℓ_a and ℓ_m are the equivalent path lengths of the magnetic flux paths in air and magnetic substrate respectively.

A_a and A_m are the corresponding equivalent cross-sectional area of the magnetic flux path. μ_m is the permeability of the magnetic substrate. If all the flux lines are confined along the surface of the substrate then

$$\ell_a = \ell_m = \ell/2$$

and

$$A_a = A_m = A$$

$$L' = \frac{2A}{\ell} \quad \frac{0.4\pi n^2}{1 + \frac{1}{\mu_m}}$$

If $\mu_m >> 1$, then $L' \simeq 2L$. Therefore the theoretical maximum increase in inductance is 100%. In the actual inductor there are flux lines away from the substrate surface and $\ell_a > \ell_m$ and the increase in inductance is less than 100%.

7.0 MEASUREMENT OF THE PARAMETERS OF THE INDUCTOR

The following parameters of the thin film inductor have been measured. The methods used for these measurements are described in the following:

7.1 D.C. RESISTANCE MEASUREMENT

Since the D.C. resistance of most thin film inductors is only a fraction of an ohm, resistance measurement at the two terminations using a two-point method is inaccurate due to contact resistances at the points of the probes. A four-point method is preferred which is shown in Fig. 7.1-1. The current used for the D.C. resistance measurement was kept low (50 ma.) to prevent heating of the inductor.

7.2 INDUCTANCE MEASUREMENT

Several methods have been used to measure the inductance of the thin film inductors. Different methods were used for the reasons that correlation among them would indicate the validity of the results and the difficulty to cover a wide frequency range with a single method. The methods used are described in the following:

7.2.1 Q-METER MEASUREMENT

A Hewlett-Packard Model 4342A Q-Meter was used to measure the inductance at about 50 MHz. For inductance values of less than 250 nh, a work coil is connected in series with the inductor to be measured. The value of the tuning capacitor is

C_1 at resonance. Then the inductor is replaced by a shorting bar and the tuning capacitor value for resonance is C_2. The value of the inductor is given by

$$L = \frac{C_2 - C_1}{\omega^2 C_1 C_2}$$

where ω is the angular frequency of the measurement. The inductance of the shorting bar is neglected since it is small compared to the residual inductance in the Q-Meter.

It should be noted that in the Q-Meter the measurement is made in series resonance and therefore the inductance measured is the effective inductance due to the distributed capacitance in the inductor. The effective inductance is

$$L_e = \frac{L}{1-(\frac{\omega}{\omega_o})^2}$$

where ω_o the resonant angular frequency. If the self-resonant frequency is much greater than the measuring frequency the effective inductance is almost equal to the intrinsic inductance. For inductances greater than 250 nh the measurement is made without the work coil. The residual inductance in the Q-meter is approximately 10 nh which is to be substracted from the measured values.

7.2.2 SWEEP FREQUENCY METHOD

The block diagram of the sweep frequency method is shown in Fig. 7.2.2.-1. The sweep frequency generator output is terminated by a 50 Ω resistor and drives the inductor and crystal detector in series. At frequencies near resonance the impedance of the inductor is $Q\omega L$ which in most cases is much greater than 50 Ω so the sweep frequency generator sees approximately 50 Ω . The voltage across the crystal detector which has an impedance of 50 Ω is proportional to the current through the inductor. At the resonant frequency of the inductor, the impedance of the parallel resonant circuit (L and C_d + C) has the maximum value and the output of the crystal detector is at a minimum. When the external capacitor C is zero, the frequency ω_o at which the minimum occurs is the self resonant frequency. C_d represents the distributed capacitance of the inductor. With the external capacitance C connected the resonant frequency will be lowered to ω_1.

The inductance L is given by

$$L = \frac{\omega_o^2 - \omega_1^2}{C_1 \omega_o^2 \omega_1^2}$$

In this method the inductance measured is the intrinsic inductance since the inductance is in parallel resonance with the capacitance.

7.2.3 NETWORK ANALYZER

In this method the inductor is connected at the load end of a transmission line. The impedance of the inductor can be computed from the reflection coefficient Γ

$$Z_L = Z_o \frac{1+\Gamma}{1-\Gamma}$$

Z_o is the characteristic impedance of the transmission line which is usually 50 Ω resistive. The calculation is facilitated by using a Smith Chart. The impedance

$$Z_L = R + jX$$

and $X = \omega L_e$, L_e is the effective inductance as mentioned in the Q-Meter test (Sec. 7.2.1). Measurement using this method has been carried out using a Hewlett-Packard Automatic Network Analyzer Model 8507A and a Model 11608A Transistor Fixture in the laboratory of the Naval Air Development Center.

7.2.4 RX-METER

RX-Meter such as the Boonton Radio Corp. Model 250-A can be used to measure the impedance of an inductor. The measurement is given as equivalent parallel reactance, X_p and resistance, R_p at a given frequency. The frequency range of the Model 250-A is 0.5 to 250 MHz.

7.3 Q-FACTOR MEASUREMENT

As in the inductance measurements there are many ways for measuring the Q-factor. The various methods described in the following have been used for the purpose of correlation.

7.3.1 Q-METER METHOD

At low frequencies (up to 70 MHz) the Q factor can be measured on the Hewlett-Packard Model 4342A Q-Meter. For inductors up to 250 nh the Q is measured with a series work coil in the same manner as the inductance measurement. The Q-factor is given by

$$Q_e = \frac{Q_1 \, Q_2 \, (C_1 - C_2)}{C_1 \, Q_1 - C_2 \, Q_2}$$

where C_1 and Q_1 are tuning capacitor value and Q reading on the Q-Meter respectively with a shorting bar. C_2 and Q_2 are the corresponding readings when the inductor is connected.

It should be noted that the value of Q measured is the effective value which relates to the intrinsic Q by

$$Q_e = Q \left(1 - \frac{\omega^2}{\omega_o^2}\right)$$

which becomes zero at the self-resonant frequency. This effect should be taken into account when ω_o is close to the measuring frequency.

For inductances greater than 250 nh, the Q-factor can be measured without a series work coil, however, it is not advisable to do so due to the resistances in the Q-meter test jig and contacts.

7.3.2 SWEEP FREQUENCY METHOD

The same setup as described in Sec. 7.2.2 is used to measure the Q-factors of the inductors. The output of the crystal detector is displayed on an oscilloscope as shown in Fig. 7.3.2-1. If the impedance of the inductor, Z_L is much greater than 50 ohms, the curve shown represents the current in Z_L and it is the reciprocal of Z_L. The 3 db line as shown in Fig. 7.3.2-1 intersects the curve at 3db points, then the value of Q is

$$Q = \frac{fo}{f_2 - f_1}$$

To obtain the value of Q at lower frequencies than the self-resonant frequency, external capacitors, C is connected in parallel with the inductor. The Q measured is the intrinsic Q since the inductance is in parallel resonance with capacitors.

7.3.3 IMPEDANCE METHOD

Using the same test setup as in the last Section above except that the sweep frequency generator is in CW mode. The minimum output of the crystal detector at resonance is V_o and V_1 is the output of the crystal detector when the inductor is shorted by a shorting bar. The Q-factor can be calculated from

$$Q = \frac{75V_1 - 50\ V_o}{2\pi\ f\ L\ V_o}$$

where the inductance L is measured by any of the methods described previously.

7.3.4 NETWORK ANALYZER, REFLECTION MEASUREMENT

Same method described in Sec. 7.2.3 will also give the value of Q

$$Q_e = \frac{X}{R}$$

which is the effective value of Q as discussed before.

7.3.5 NETWORK ANALYZER, TRANSMISSION MEASUREMENT

For the transmission measurement the inductor is inserted in series with the transmission line by using a special jig. The maximum insertion loss occurs at the resonant frequency. The impedance of the inductor at resonance is $Q\omega L$ and is resistive. The insertion loss is

$$A = 20 \log_{10} \frac{E_{out}}{E_{in}}$$

where

$$\frac{E_{out}}{E_{in}} = \frac{50}{Q\omega L + 50}$$

Q factor can be calculated if L is known. The Q factor measured in this method is the intrinsic value since the inductor is in parallel resonance with its distributed capacitance and external capacitance, if any.

Alternatively the Q-factor can be obtained from the attenuation curve vs. frequency as in the method described in

Sec. 7.3.2. The frequency between two 3db points with respect to the value at the resonant frequency, fo is Δf and the Q-factor is

$$Q = \frac{fo}{\Delta f}$$

7.4 CORRELATION OF MEASURED PARAMETERS BY DIFFERENT METHODS

The measurements of the inductance and Q-factor by various methods are influenced by many factors such as contact resistances, parasitic inductance and capacitances, non-linearity in crystal detector response, impedance mismatch, etc. Consequently, the results of the measurements by various methods differed considerably in some cases. The comparisons of the measured values by different methods were further compromised by the fact that not all methods can cover the same frequency range due to their limitations. This is an important factor for Q measurements, since the Q-value is a function of frequency.

The following is a list of values measured by various methods. An L-55c inductor was used for all the measurements made.

7.4.1 RESULTS OF INDUCTANCE MEASUREMENT

The intrinsic inductance of an L-55c inductor was measured by various methods described above and the results are as follows:

1.	Q-Meter at 50 MHz	23.0 nh
2.	Sweep Frequency Tester at 475 MHz	22.1 nh
3.	RX-Meter at 250 MHz	30.3 nh
4.	Network Analyzer at 50 MHz	23.8 nh
	at 250 MHz	19.4 nh

The instruments used in the above measurements were as follows:

1.	Q-Meter:	Hewlett-Packard Model 4342A
2.	Sweep Frequency Tester:	Designed & Built by Thinco
3.	RX-Meter:	Booton Radio Corp. Model 250-A
4.	Network Analyzer:	Hewlett-Packard Model 8507A and Transistor Fixture Model 11608A

It should be noted that all the values of inductance given above are the intrinsic values and should be independent of frequency. The values measured by the Sweep Frequency Tester and Network Analyzer at 50 MHz agree within 5% of that obtained from Q-Meter measurement. The values measured by RX-Meter and Network Analyzer at 250 MHz showed large discrepancies. The low value obtained by Network Analyzer at 250 MHz is probably due to the stray capacitances in the Transistor Fixture used in the inductor measurement. The cause of the large inductance value given by the RX Meter is not known.

It appears that the Q-Meter would be the preferred for measuring intrinsic inductance. Since 50 MHz is much lower than the self-resonant frequency in most cases the measured value is very close to the intrinsic value.

7.4.2 RESULTS OF Q-FACTOR MEASUREMENT

The Q-factor of an L-55c inductor was measured by various methods described above and the results are as follows:

1.	Q-Meter	7.4	at	50 MHz
2.	Sweep Frequency Tester, 3db points	35.8	at	342 MHz
		41.6	at	431 MHz
		30.9	at	518 MHz
		28.7	at	758 MHz
3.	Sweep Frequency Tester, Impendance Ratio	54.4	at	342 MHz
4.	RX-Meter	21.4	at	250 MHz
5.	Network Analyzer, Reflection Measurement	6.0	at	50 MHz
		9.6	at	250 MHz
		8.9	at	450 MHz
6.	Network Analyzer, Transmission Measurement: (a) From insertion loss at resonance	6.7	at	738 MHz
	(b) From 3db points of resonance curve	15.9	at	738 MHz

Large discrepancies exist among the results of Q-factor measurements due to a number of factors. Since Q-factor is a function of frequency and the frequency ranges of different method are not the same, it makes the direct comparison more difficult. Some of the possible causes of these divergent results are:

Parasitic capacitances and inductances of test jig.
Contact resistances of test jig.
Non-linearity of crystal detector.

From the results of experiments it appears that for inductance measurement the Q-Meter method is preferred and for Q measurements in the frequency range of 100 MHz to 1 GHz

The Sweep Frequency Tester using the 3db points of the impedance curve seems to give reasonable results. It also provides the capability of connecting an external chip capacitor in parallel with the inductor for measuring the Q-factor at frequencies lower than the self-resonant frequency. The test jig in the Network Analyzer cannot accomodate chip capacitors in parallel with the inductor under test.

The higher value of Q measured by the impedance ratio method using the Sweep Frequency Tester is due to the nonlinearity of the crystal detector at low signal levels (below 5 mv.).

8.0 CONCLUSIONS

In the course of this development the Q-factor and the self-resonant frequency have been considerably increased. These improvements were realized by the proper choice of geometry, utilization of low-loss dielectric material, and precise masking techniques.

Using the specially developed ferrite as substrate, an increase in inductance and Q-factor of up to 60% and an inductance of greater than 1 microhenry have been achieved. The Following is a list of inductors fabricated using these techniques:

Inductance Type	No of Turns	Inductance nh (1)	Self-Resonant Freq. MHz(2)	Q-Factor @ MHz(2)
L-55c	3½	24	810	54 @ 260 69 @ 460 59 @ 810
L-55c	5½	53	640	45 @ 180 41 @ 340 28 @ 640
L-55c	6½	73	520	29 @ 260 31 @ 320 30 @ 520
L-55c	7½	98	450	35 @ 140 31 @ 250 34 @ 450
L-55cf (3)	14½	475	210	100 @ 60 70 @ 102 60 @ 125
L-100c	8½	250	185	55 @ 100
L-100c	12½	500	147	63 @ 107
L-100cf (3)	12½	825	98	105 @ 50
L-100cf (3)	14½	1,125	87	31 @ 65

(1) Measured by H-P 4342A Q-Meter
(2) Measured by Thinco Sweep Frequency Tester
(3) Ferrite Substrate

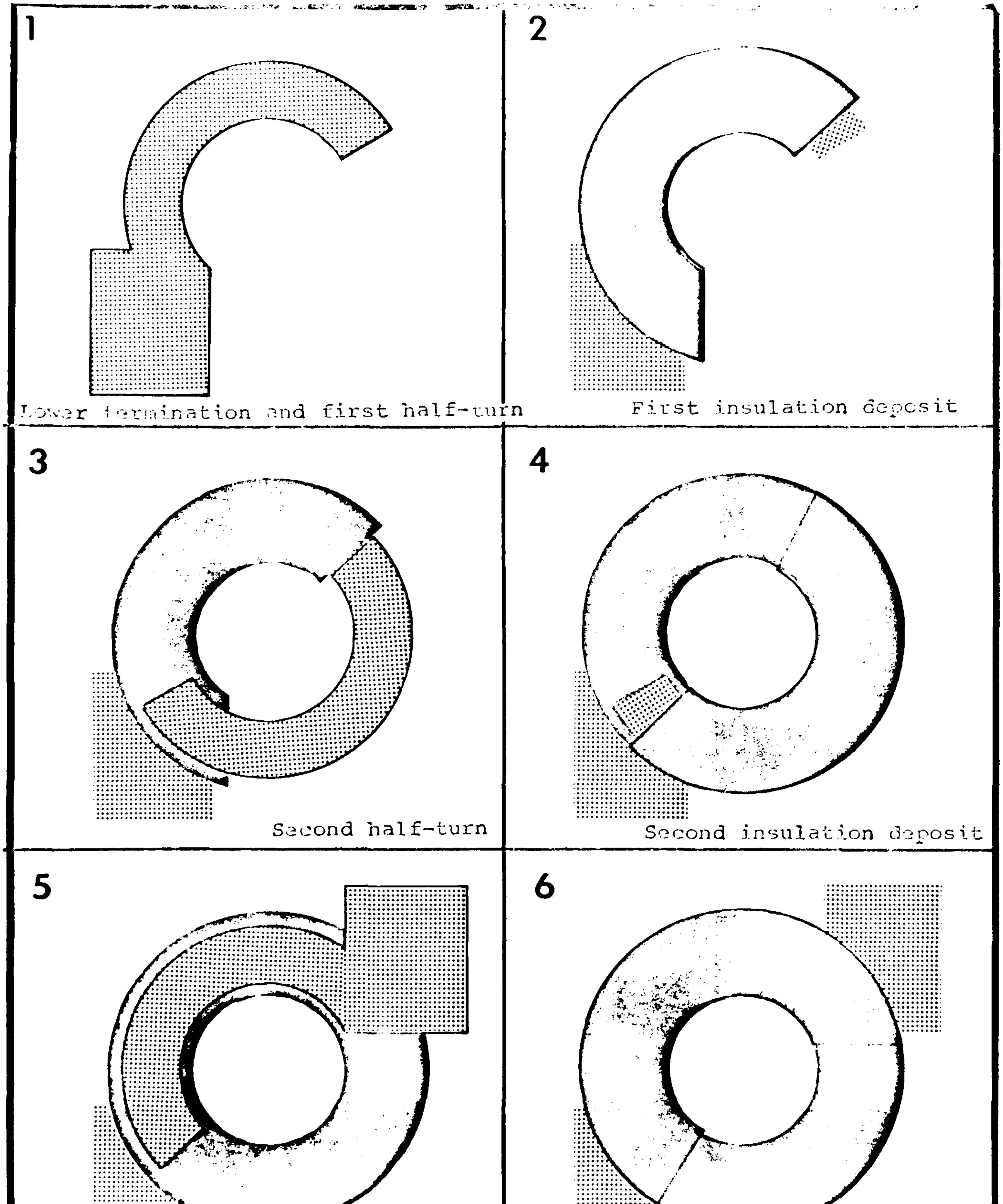
1
Lower termination and first half-turn
2
First insulation deposit
3
Second half-turn
4
Second insulation deposit
5
Final
half-turn and upper termination
6
Final insulation deposit

Fig. 1.0-1

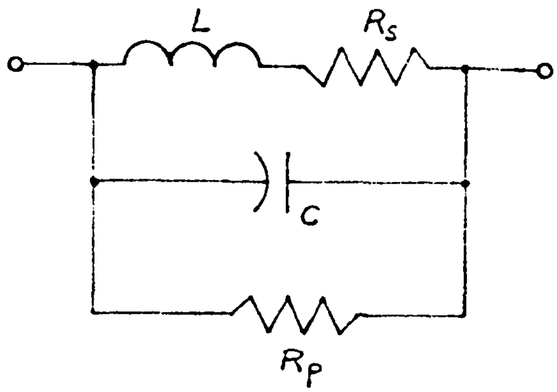

Fig. 2.1-1. Equivalent Circuit of an Inductor

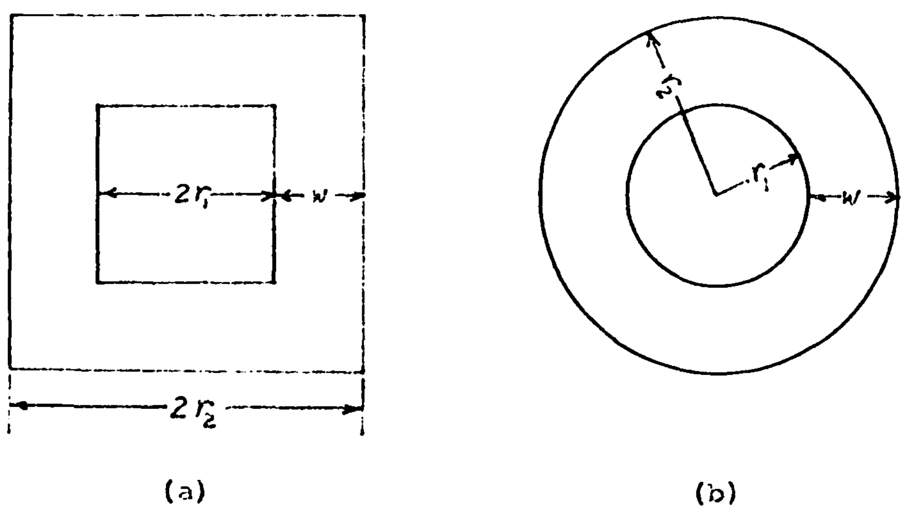

Fig. 3.0-1. Geometry of Inductor:
(a) Square
(b) Circular

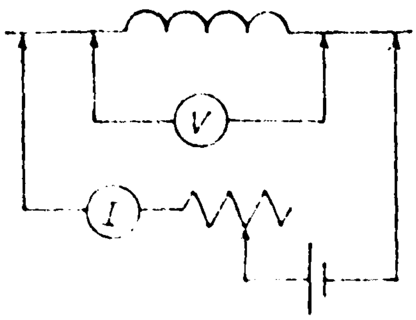

Fig. 7.1-1 Resistance Measurement using the Four-Point Method

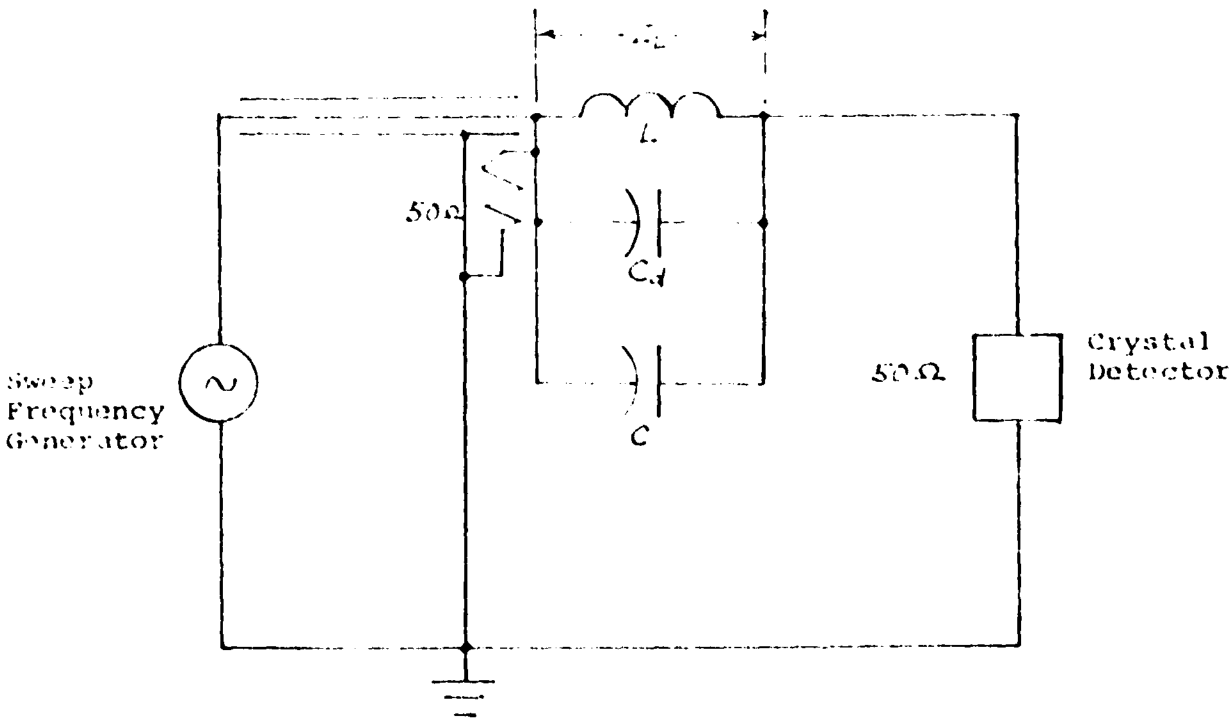

Fig. 7.2.2-1

Sweep Frequency Test Set

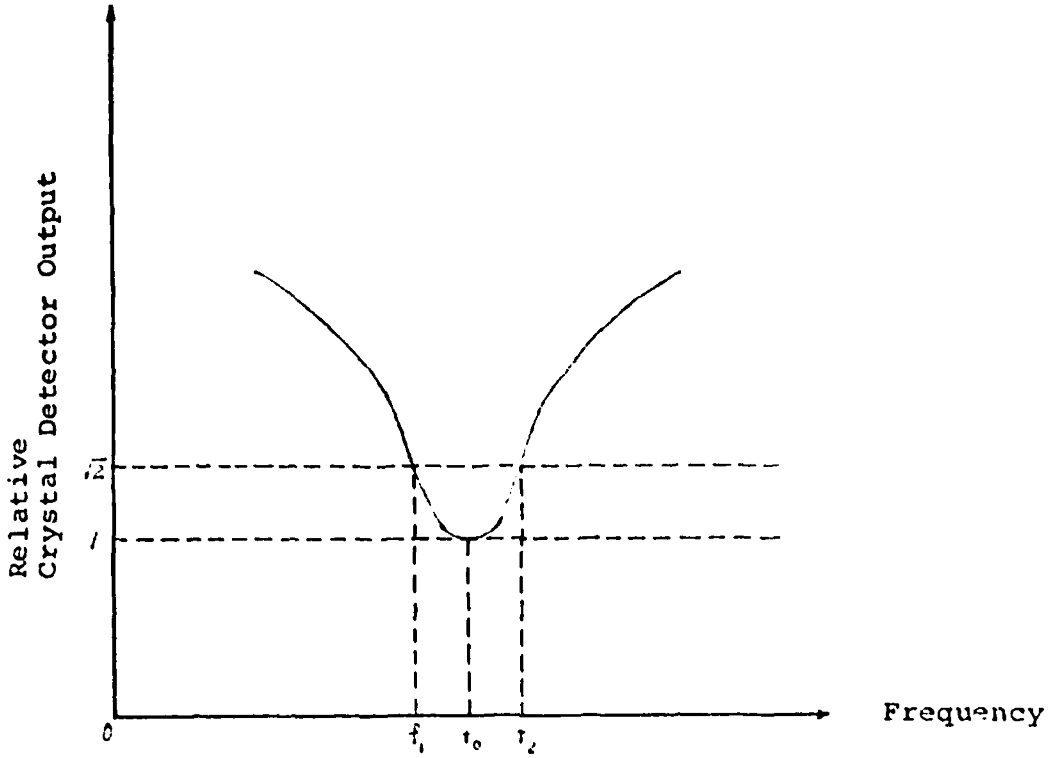

Fig. 7.3.2-1
Impedane of Inductor versus Frequency